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Prospective energy security scenarios in Spain: The future role of renewable power generation technologies and climate change implications

Diego García-Gusano, Diego Iribarren*

Systems Analysis Unit, IMDEA Energy, E-28935, Móstoles, Spain

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ABSTRACT

Energy security is a complex issue that arises as one of the main concerns for most of the countries when regarding the future. In this sense, given the acknowledged lack of future-oriented studies in this field, this article performs a prospective analysis of the energy security of a national energy system. This is done through a novel methodological framework combining Life Cycle Assessment and Energy Systems Modelling. In particular, the recently proposed Renewable Energy Security Index (RESI) is endogenously integrated into a national power generation model in order to prospectively evaluate the energy security of the Spanish electricity production mix. This facilitates the exploration of alternative energy security scenarios based on RESI targets and focused on the penetration of renewables. The results show that, despite the relatively high renewable contribution reached in a business-as-usual scenario, a significantly higher and faster renewable penetration is attained when implementing RESI targets of 70%, 80% and 90% by 2030 in Spain. This is found to be associated with a large deployment of (onshore and offshore) wind power generation technology. Finally, a favourable life-cycle climate change performance is found when pursuing ambitious energy security targets.

1. Introduction

It is commonly accepted that efforts in facing climate change will lead to advances in energy security as a co-benefit. Although this rationale appears to be realistic, some authors have started to question it [1]. Moreover, it should be noted that policy targets are not limited to climate change and/or energy security [2]. There are additional issues concerning environmental pollution, air quality, economic development, social equity, etc., which cannot be thought separately since they refer mainly to the same problem: how to satisfy an increasing energy demand –driven by the economic growth– with optimal supply, i.e. minimising total system costs while respecting the sustainability goal. However, there is a lack of scientific works encompassing climate change and energy security concerns, especially from a prospective angle. In this sense, inspired by the results reported by Jewell et al. [1] on the fact that it is not necessarily true that pursuing a climate change target leads directly to significant increases in energy independence, the present paper performs a reverse analysis. Thus, the effects of pursuing energy security targets on the evolution of climate change and the penetration of renewables were evaluated using a national energy systems optimisation model enriched with life-cycle indicators.

Scientific tools oriented towards enhanced energy policy-making require a trade-off between practicality and comprehensiveness. There are thousands of works discussing climate change issues, most of them focused on specific technologies [3], fuels [4], sectors [5,6] or regions [7,8] with the aim of reducing greenhouse gas (GHG) emissions, thereby mitigating climate change effects. Additionally, there is a significant amount of works dealing with energy security at both regional and global levels. For instance, Kruyt et al. [9] carried out a detailed review of studies on energy security using the model TIMER to make prospective assessments, while Löschel et al. [10] and Ang et al. [11] thoroughly discussed the different aspects covered within the energy security literature. Furthermore, Månsson et al. [12] performed an overview of commonly used methodologies to assess energy security, concluding that methodological hybridisation may be a solution to face the multidisciplinary concern. Despite analysing several

* Corresponding author.
E-mail address: diego.iribarren@imdea.org (D. Iribarren).

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experiences in the field of energy security indicators [13–16], it was observed that a significant number of authors carry out prospective energy scenarios without quantifying energy security indicators but discussing them in a subjective manner. In a central document, the Asia Pacific Energy Research Centre [17] carried out a report on the interactions between energy security and climate change policies evaluating measures that appear to be effective for both purposes but without merging the concepts in depth.

According to Umbach [18], the concept of national energy security depends on the specific location, regional policies, and the traditional economic and business ties. It is accepted that climate change could be an accelerant of conflicts due to its consequences in many places across the globe. Direct consequences could be casualties due to extreme hurricanes or floods, whereas indirect damages would be associated with e.g. desertification –and its consequences such as migrations, ecosystem destruction and resource wars– in sensible areas. Regarding direct effects on energy security, it is worth mentioning the oil production decrease in the USA attributable to Hurricane Katrina in 2005, which affected significantly the global oil prices and international policies during the following months [19]. Although the scientific research regarding energy security uses indicators to measure specific aspects of the security such as accessibility, security of supply, affordability and sustainability performance, it fails when it comes to giving a holistic, wide-ranging approach. Moreover, most of the available studies are merely retrospective (based on historical data). For instance, the relevant works by Martchamadol and Kumar [20] and the Institute for 21st Century Energy [21] developed sound indicators for retrospective analysis, including numerous issues related to energy security: fuel prices, imports, macro-economic indicators performance, energy intensity, CO_2 emissions, etc.

Within this context, the present article was conceived as an exploration of the connection between energy security and climate change from a prospective viewpoint, thus dealing with the underdeveloped field of future-oriented energy security assessment [12]. This was conducted for the case study of power generation in Spain through the endogenous integration of life-cycle indicators of current and future electricity production technologies into the specific energy systems model developed by García-Gusano et al. [22]. In particular, besides the integration of climate change as a holistic indicator (i.e., an indicator that considers that the parts of a system are intimately interconnected and explicable only by reference to the whole system), the life cycle-based "renewable energy security index" –RESI [23]– was also endogenised (Section 2). Therefore, this article deals with the challenging task of prospective energy scenario modelling in terms of energy security, additionally exploring the coherence –concerning climate change implications– of the effects of pursuing energy security targets rather than GHG reductions [24].

The novelty of the work is based on its prospective nature as well as on the way energy security was considered. First, the reverse notion of energy security as the initial motivator is innovative, especially looking at the rationale behind most of the energy planning models such as MARKAL/TIMES [25], LEAP [26], MESSAGE [27], etc. Second, the novel use of RESI allows analysts to tackle key energy security aspects such as affordability, availability, indigenous resources and sustainability in a comprehensive, easy-to-report index [23,28]. Third, the endogenous integration of life-cycle indicators into an energy systems model broadens the capabilities of analysts to study the evolution of this type of indicators (in particular, climate change) [22]. Finally, the endogenisation –for the first time– of RESI targets enables the prospective assessment of alternative energy security scenarios by directly affecting the optimisation procedure of minimising the total system costs, in contrast to previous studies [23].

It should be noted that the case study of Spain was selected because –besides the availability of a detailed and updated national energy systems model for power generation [22]– this country accounts for a varied portfolio of technologies within its electricity production mix (nuclear power, wind power, hydropower, coal, natural gas, etc.) [29]. In this respect, this article aims to facilitate energy policy-making processes by prospectively assessing the suitability of energy security targets not only in terms of climate change but also regarding a higher and faster penetration of renewable power generation technologies.

2. Materials and methods

In order to pave the way for more comprehensive energy policies, it is necessary to enhance the traditional approach to energy systems modelling (ESM). In this regard, the joint use of Life Cycle Assessment (LCA) and ESM methodologies is a growing research area that brings new opportunities for both LCA practitioners –adding a prospective dimension to their studies– and energy modellers –enriching the optimisation procedure with underdeveloped aspects related to sustainability and energy security.

García-Gusano et al. [30] discussed the first steps towards the endogenisation of life-cycle sustainability indicators in national energy systems models. Following a similar rationale, this article additionally integrates energy security into the optimisation problem as a life cycle-based component of the power generation technologies. Regarding the techno-economic component of the energy system (Section 2.1), a LEAP-OSeMOSYS model focused on the Spanish power generation sector was used [22]. The integration of the energy security component into the ESM framework was carried out through an energy policy-oriented index, RESI (Section 2.2), which has recently been proven to be a practical but wide-ranging index to develop prospective energy security scenarios [23,28]. Fig. 1 represents the RESI endogenisation framework designed in this study.

The multi-method framework in Fig. 1 means a significant enhancement of the original LCA + ESM approaches in Refs. [22,30], which address the endogenisation of life-cycle sustainability indicators of the power generation technologies but putting energy security on the back burner. The present article goes deeper by carrying out a double endogenisation process in order to cope with

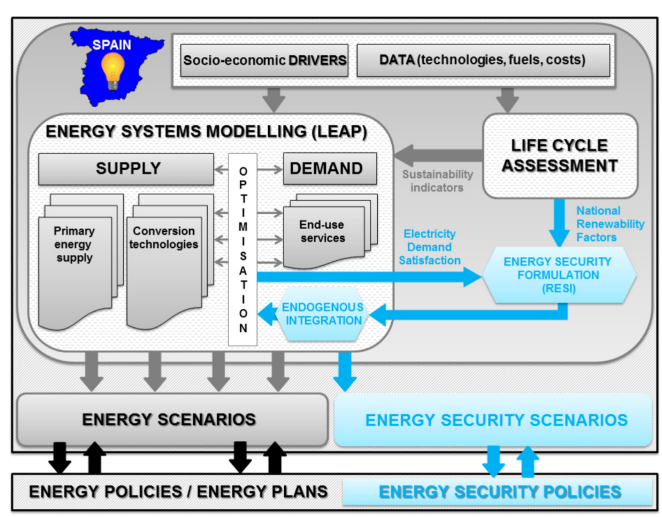

Fig. 1. Endogenisation of energy security in power generation models for energy planning.

both energy security and sustainability issues from a prospective standpoint. In this respect, in addition to the endogenisation of life-cycle indicators (in particular, climate change), RESI targets were singularly endogenised by implementing the original formulation of RESI [23] in the core of the optimisation-based ESM framework as a user constraint (Section 2.3). Hence, the endogenisation of RESI allows not only the analysis of the evolution of this life cycle-based index but also the analysis of the effect of imposing energy security targets that affect the optimisation problem. This constitutes an interesting option for energy planners, especially looking at the substantial penetration of renewable energy technologies expected in the long term [31,32].

2.1. Techno-economic approach

As shown in Fig. 1, the techno-economic component of the analysis is driven by ESM. The LEAP-OSeMOSYS model available for power generation in Spain was used [22]. This combination of ESM frameworks is bottom-up, technology-rich and oriented towards energy planners and policy-makers for the development of sustainable plans. While LEAP (Long-range Energy Alternatives Planning system) is originally conceived as a simulation-based accounting framework for the design of energy policies from a backcasting approach [26], the addition of OSeMOSYS (Open Source energy Modelling System) —a well-known systems optimisation model generator for long-run integrated assessment and energy planning— enables the development of forecasting approaches by minimising total system costs [33].

Thus, the combination of both modelling tools —LEAP and OSeMOSYS— facilitates the exploration of the optimal electricity production mixes that would satisfy the exogenous electricity demands associated with the end-use energy services in the different economic sectors (transport, industry, residential sector, service sector, and agriculture). Technical (e.g., efficiencies and capacity factors) and economic (e.g., investment costs, fixed and variable costs, and fuel costs) data of the electricity generation technologies come mainly from the European Commission [34]. Finally, further details about the LEAP-OSeMOSYS model for power generation in Spain —including the key techno-economic parameters of the electricity production technologies involved— are available in Ref. [22].

2.2. Life-cycle approach to energy security

The goal of this work is to assess energy security in a holistic and prospective way. Accordingly, the life cycle-based index RESI —originally formulated by García-Gusano et al. [23] in the context of several national ESM frameworks— was selected. RESI allows the discussion of a wide range of topics related to energy security: demand satisfaction, energy independence, resource availability, affordability, etc. In fact, *RESI* for a period *j* is defined by Eq. (1) as the summation of the product of the electricity demand satisfaction (*EDS*) and the national (i.e., indigenous) renewability factor (*NRF*) for each power generation technology *i*:

$$RESI_j = \sum_i EDS_{i,j} \cdot NRF_i \tag{1}$$

On the one hand, regarding the techno-economic component of the index, EDS covers the share of the electricity demand satisfied by each power generation technology installed in a specific country. On the other hand, NRF involves a life-cycle perspective since it is defined as the ratio of the cumulative energy demand associated with indigenous renewable sources (CED_{r_ind}) to the total cumulative energy demand (CED_t) of each electricity production technology in the national mix.

In order to calculate the NRF values of the technologies, specific LCA studies were carried out. Starting from the definition and the inventories of the power generation systems as detailed in Ref. [22], the life cycle impact assessment of each technology was performed by using the software SimaPro [35] and the VDI method [36] for the calculation of cumulative energy demand (CED) indicators: CED_t, non-renewable CED (fossil and nuclear), and renewable CED (CED_r, involving solar, geothermal, wind, water and biomass resources). Furthermore, the CED_r indicator restricted to indigenous renewable resources was calculated, i.e. CED_{r_ind}. Subsequently, the NRF values presented in Table 1 were computed as the ratio of CED_{r_ind} to CED_t. It should be noted that the NRF values involve both techno-environmental aspects —through the life cycle energy analysis— and energy security aspects —through the specific consideration of indigenous renewable resources [23]. In line with the original study [22], which endogenises the climate change indicator evaluated through the IMPACT 2002+ method [37], the LCA studies of the power generation technologies followed a cradle-to-gate approach (from raw material extraction to electricity production) and set a functional unit of 1 MWh of electricity produced.

The values in Table 1 show that both fossil and nuclear technologies score zero because of their non-renewable origin. Nevertheless, cogeneration plants (existing and new) score 5% and 27% due to the partial use of biomass. Finally, it was observed that existing technologies generally score better than their corresponding new option, which is due to their different level of consumption in terms of indigenous renewable resources.

2.3. Endogenisation of energy security

RESI is a valid indicator for both retrospective and prospective assessment of national energy security. In particular, prospective

Table 1
National Renewability Factors (NRF) of the power generation technologies relevant to the defined scenarios.

Technology	NRF (%)
Existing coal thermal	0.00
Existing oil combustion engine	0.00
Existing natural gas combined cycle (NGCC)	0.00
Existing cogeneration	5.11
Existing nuclear – boiling water reactor (BWR)	0.00
Existing nuclear – pressurised water reactor (PWR)	0.00
Existing hydropower – dam	98.51
Existing hydropower – run-of-river (RoR)	98.86
Existing wind – onshore	95.56
Existing solar photovoltaics (PV)	80.42
Existing solar thermal	80.53
Existing biomass power plant	96.41
Existing waste-to-energy plant	96.00
Existing biogas power plant	93.62
New NGCC	0.00
New NGCC with CO_2 capture	0.00
New cogeneration	26.73
New wind – onshore	96.98
New wind – offshore	93.47
New solar PV – plant	87.14
New solar PV – roof	89.04
New solar thermal with storage	78.40
New biomass power plant	95.46
New waste-to-energy plant	94.60
New biogas power plant	80.09
New geothermal power plant	98.65
New wave power plant	90.60
New solid oxide fuel cells (SOFC)	0.00

analyses would benefit from the endogenous integration of RESI into ESM frameworks, which was undertaken herein. Taking advantage of the renewable electricity production constraints developed by Howells et al. [33] in OSeMOSYS, it was possible to endogenise RESI targets in the LEAP-OSeMOSYS model for power generation in Spain, thus affecting directly the optimisation procedure.

Coming from the general definition of RESI in Eq. (1), the extended version of RESI is formulated in Eq. (2):

$$RESI_j = \beta \cdot \sum_i \frac{EP_{i,j} \cdot CED_{r\_ind,i}}{NED_j \cdot CED_{t,i}} \tag{2}$$

Values from Eq. (2) are typically below 1. The sub-index *i* refers to each power generation technology while *j* stands for each time step in the optimisation routine. In the Spanish case study, electricity production (*EP*) and national electricity demand (*NED*) tend to be similar [28]. Additionally, the β coefficient allows the implementation of divergences and corrections such as the non-zero import/export balance and transmission losses [23]. In this article, β was assumed to be 0.98 according to the historical data of the Spanish electricity system [29]. Nevertheless, while the NRF component (CED_{r_ind} to CED_t ratio) is always below 1, the EDS side (characterised by EP, NED and β) might be above 1 if more electricity than needed is produced [23].

According to the extended formulation of RESI, and given the fact that NRF values can be directly endogenised in the energy systems model as a quantitative measure of "renewable qualification" [26], the renewable production targets already available in the LEAP-OSeMOSYS framework [26,33] actually correspond to endogenous RESI targets. This comes in addition to the life-cycle indicators already endogenised in the LEAP-OSeMOSYS model for power generation in Spain (which includes, among others, climate change) [22].

2.4. Energy security scenarios

In order to perform the prospective assessment of energy security in the Spanish power generation sector, alternative scenarios were explored. First, a reference (business-as-usual, BaU) scenario was considered in accordance with the available literature [22]. Then, three additional scenarios were developed to test the consequences of setting national RESI targets in energy policies. Table 2 presents the definition of the assessed scenarios.

The rationale behind these exploratory scenarios relies on fixing sensible RESI targets by 2030 (milestone year) [23,28], subsequently discussing the effects of this security-based approach on the evolution of the entire Spanish electricity system, mainly in terms of penetration of renewables and climate change implications.

3. Results and discussion

3.1. Electricity production: the role of renewables

This section addresses the evolution of the Spanish electricity production at the technology level, with emphasis on the competition between renewable and non-renewable technologies not only in the BaU scenario (Section 3.1.1) but also in alternative energy security scenarios (Section 3.1.2).

3.1.1. BaU scenario

Electricity production is a key variable analysed in ESM studies. Fig. 2 shows the evolution of power generation in Spain by technology in the period 2010–2050. Although the reference year of the study is 2010, electricity production data for the period 2010–2015 correspond to historical data in order to increase the accuracy of the model [22].

Fig. 2 shows a transition from existing technologies to new installations involving three main steps. First, coal disappears around 2020–2023. Second, a nuclear phase-out happens in 2021–2028 provided that the authorities do not extend their operating licences beyond 40 years. Finally, NGCC plants disappear by the end of their lifetime around 2037–2040. These steps are associated with a significant penetration of renewable technologies in the Spanish electricity production mix. In this regard, even though the first new installations correspond to natural gas cogeneration plants until 2020, onshore wind and solar PV begin to grow importantly afterwards. Moreover, offshore wind emerges significantly by 2030 and there is a high penetration of concentrated solar thermal plants

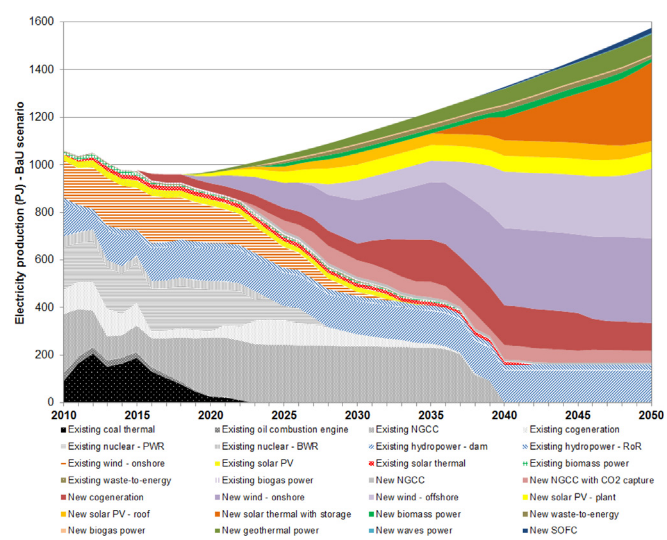

Fig. 2. Evolution of the Spanish electricity production by technology under BaU circumstances.

Table 2
Description of the energy scenarios considered in the study.

Code	Scenario	Remarks
BaU	Business-as-Usual	It includes calibrations up to 2015 regarding electricity production and capacities. It considers a 40% reduction in CO_2 emissions —with respect to 1990 levels— by 2030 at the sector level (from then on, the emission constraint is kept constant at 39 Mt CO_2 per year).
RESI_70	RESI ≥0.7 in 2030	It modifies the BaU scenario by implementing a renewable energy security target above 70% by 2030.
RESI_80	RESI ≥0.8 in 2030	It modifies the BaU scenario by implementing a renewable energy security target above 80% by 2030.
RESI_90	RESI ≥0.9 in 2030	It modifies the BaU scenario by implementing a renewable energy security target above 90% by 2030.

with storage by 2035. It should also be noted that a significant contribution from new natural gas cogeneration plants was observed from 2030 in order to meet the growing electricity demand.

The overall contribution of renewable power generation technologies to the Spanish mix was further explored. Despite the unusual trend in the period 2010–2015 –closely linked to political decisions (coal consumption grew significantly in 2015 [38])–, the prospective analysis clearly shows a significant use of renewables. A progressive growth of renewables was found in the period 2016–2030, mainly motivated by coal and nuclear retirements. A second growth phase takes place between 2035 and 2040, once existing NGCC plants start closing down. Finally, renewable electricity production in Spain reaches a contribution of 89% in 2050 in the BaU scenario.

3.1.2. Energy security scenarios

In order to understand the effects of energy security targets on electricity production, Fig. 3 shows the different contribution of renewables according to the RESI target pursued. High renewable contributions were found in the three alternative scenarios, reaching 93%, 96% and 98% in 2050 in the scenarios RESI_70, RESI_80 and RESI_90, respectively. All these values are higher than that associated with the BaU scenario (89%). In this respect, even though the Spanish electricity production mix will be –in any case– highly renewable in the long term, increasing energy security targets were found to lead to a faster and higher penetration of renewables.

Regarding the emergence of specific power generation technologies, Table 3 presents the foreseen contribution of each technology to the Spanish electricity production mix in 2016, 2030 and 2050 in the different scenarios under evaluation. It should be noted that the contributions presented for 2015 are historical, being 2016 the first modelling year. These results indicate that wind technologies play a major role, reaching in 2050 contributions of 43% in RESI_70 and 53% in RESI_90. In this sense, wind options –both onshore and (mainly) offshore– were found to be favoured by ambitious energy security targets. In contrast, concentrated solar thermal plants with storage show an opposite behaviour: the more ambitious the energy security target pursued, the lower the penetration of this technology in the mix. This is due to the presence of natural gas back-up systems that involve a penalty in terms of NRF when compared to other renewable options (Table 1).

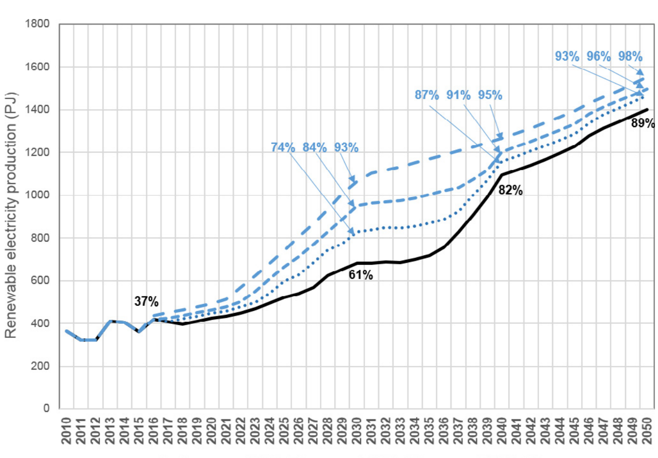

Fig. 3. Evolution of renewable power generation in Spain under alternative energy security scenarios (percentages represent the contribution of renewables with respect to total electricity production).

Finally, another relevant finding from Table 3 is the extinction of natural gas-based options from the Spanish electricity production mix when increasing energy security targets. In this regard, new NGCC, NGCC with CO_2 capture and cogeneration technologies show in 2050 contributions of only 0.2%, 1.5% and 5.3%, respectively, in the RESI_70 scenario. In fact, these contributions are reduced to negligible values in the RESI_90 scenario. Hence, ambitious targets in energy security lead to penalise natural gas options in the long term.

3.2. Energy security evolution

The emergence of renewable energy technologies, although desired, involves a great challenge for energy systems modellers since it requires a higher level of complexity than traditional, fossil-based systems. In this research area, RESI was created as a sound indicator to measure the renewable energy security of countries by using ESM capabilities [23]. In this article, the endogenisation of RESI in the core of the LEAP-OSeMOSYS model for power generation in Spain enables not only the optimisation of the electricity production mix according to energy security targets but also the direct analysis of the evolution of RESI. Thus, Fig. 4 shows the evolution of RESI in the evaluated energy scenarios.

The main trend found in all the scenarios assessed is the significant increase in energy security in the long term, moving from 0.36 in 2015 to above 0.85 in 2050. In this sense, the long-term RESI values attained are considered to be satisfactory according to the reference RESI value of 0.8 proposed in Ref. [23], especially when taking into account European countries' historical RESI values. When compared to the BaU scenario, the RESI-based scenarios show a more favourable energy security performance, especially in the medium term –which is associated with the enforcement of RESI targets by 2030. The higher this RESI target is, the better the energy security performance through the whole timeline. According to the findings in Section 3.1.2, this observation is closely linked to the high penetration of wind power generation technologies given the optimal trade-off between techno-economic and RESI aspects.

Finally, it should be noted that the counterintuitive behaviour observed in the period 2030–2035, with decreases in RESI, is mainly due to the fact that new installations –although mainly renewable– also include natural gas cogeneration plants.

3.3. Climate change evolution

The choice of setting energy security targets rather than traditional constraints such as emission limits does not impede the prospective analysis of the climate change profile of the Spanish electricity production mix. In fact, the LEAP-OSeMOSYS model for power generation in Spain includes several endogenous life-cycle sustainability indicators such as climate change and human health [22]. In particular, the inclusion of climate change enables the prospective analysis of GHG emissions from a life-cycle perspective [22,30], in contrast to traditional approaches typically limited to direct CO_2 emissions. In this sense, there are hundreds of articles addressing the evolution of the CO_2 and/or GHG emissions associated with different processes, sectors and even countries, whereas there is a significant lack of studies regarding the evolution of life-cycle indicators [39].

Fig. 5 shows the evolution of climate change in the energy scenarios evaluated. The higher the RESI value pursued, the lower the climate change is. Therefore, energy policies based on energy security targets for power generation in Spain would be in agreement with (and even exceed) climate change mitigation goals. While the BaU scenario reduces its climate change by 66% from

Table 3
Technology contribution (%) to the Spanish electricity production mix in alternative energy security scenarios.

Technology	2015	2016				2030				2050			
	All	BaU	RESI_70	RESI_80	RESI_90	BaU	RESI_70	RESI_80	RESI_90	BaU	RESI_70	RESI_80	RESI_90
New SOFC	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.2	1.3	0.0
New solar thermal with storage	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.0	19.6	18.2	14.0
New wave power plant	–	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.4	0.4
New biogas power	–	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
New waste-to-energy plant	–	0.0	0.0	0.0	0.0	1.5	2.0	2.3	2.7	0.7	0.7	0.7	0.9
New biomass power plant	–	0.0	0.0	0.0	0.0	1.6	12.0	19.7	22.2	0.9	5.1	7.7	6.7
New geothermal power plant	–	0.0	0.0	0.0	0.3	3.2	3.4	3.5	3.9	5.5	5.4	5.4	5.8
New solar PV – roof	–	0.0	0.0	0.0	0.0	4.3	4.3	4.5	4.7	3.0	2.3	2.2	2.1
New solar PV – plant	–	0.0	0.0	0.0	0.0	5.9	5.9	5.9	5.8	4.4	4.4	4.4	4.4
New wind – offshore	–	0.0	0.0	0.0	0.0	7.5	8.0	9.3	14.5	18.6	19.0	19.3	26.2
New wind – onshore	–	0.0	0.0	0.0	1.6	16.1	17.5	18.8	19.7	22.6	24.3	24.7	26.8
New cogeneration	–	2.9	2.4	2.9	2.9	6.3	6.3	6.3	4.7	7.5	5.3	4.2	2.2
New NGCC with CO_2 capture	–	0.0	0.0	0.0	0.0	6.3	0.3	0.0	0.0	3.2	1.5	0.6	0.0
New NGCC	–	0.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	0.4	0.2	0.2	0.1
Existing biogas power plant	0.4	0.5	0.5	0.5	0.5	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.0
Existing waste-to-energy plant	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.0	0.0	0.0	0.0
Existing biomass power plant	1.4	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
Existing solar thermal	1.9	1.9	1.9	1.9	1.9	1.3	1.3	1.3	1.3	0.0	0.0	0.0	0.0
Existing solar PV	3.0	3.0	3.0	3.0	3.0	1.8	1.8	1.8	1.8	0.0	0.0	0.0	0.0
Existing wind – onshore	17.8	20.5	20.5	20.5	20.5	1.5	1.5	1.5	1.5	0.0	0.0	0.0	0.0
Existing hydropower – RoR	2.1	2.3	2.3	2.3	2.3	2.0	2.0	2.0	1.9	1.4	1.4	1.4	1.4
Existing hydropower – dam	9.5	14.4	14.4	14.4	14.4	12.3	12.3	12.3	12.0	8.8	8.8	8.8	8.7
Existing nuclear – BWR	2.7	3.5	3.5	3.5	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Existing nuclear – PWR	17.4	18.4	18.4	18.4	18.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Existing cogeneration	10.0	3.5	3.8	3.5	2.5	4.6	1.4	0.0	0.0	0.0	0.0	0.0	0.0
Existing NGCC	11.1	12.4	12.4	12.4	12.4	21.2	17.3	8.3	1.8	0.0	0.0	0.0	0.0
Existing oil combustion engine	2.5	1.9	1.9	1.9	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Existing coal thermal	19.4	13.8	14.0	13.8	12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

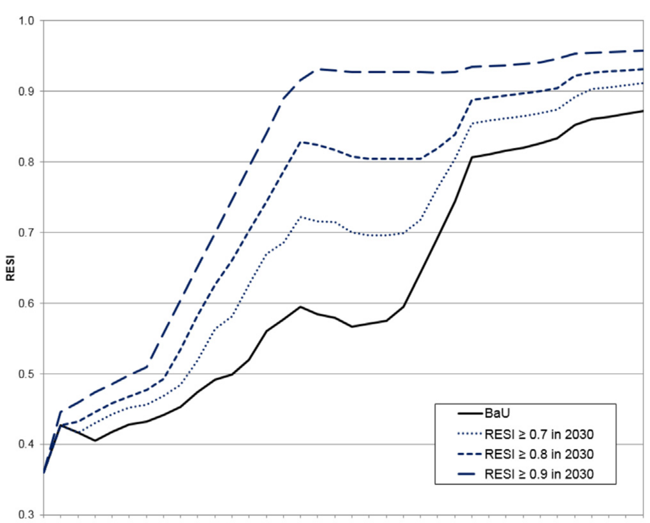

Fig. 4. RESI evolution in alternative energy security scenarios.

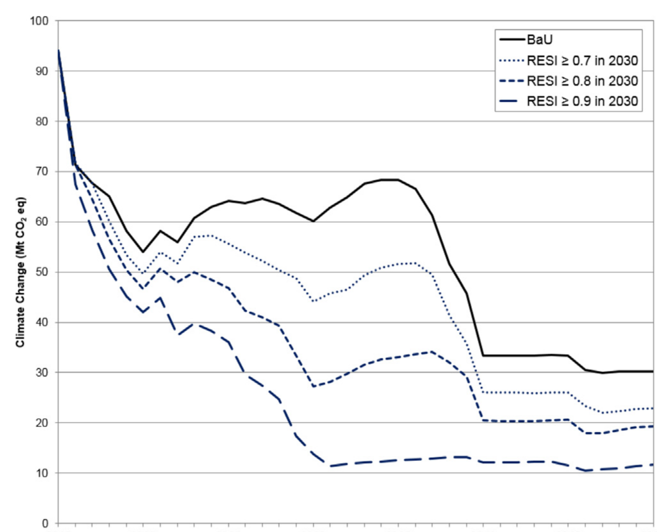

Fig. 5. Climate change evolution in alternative energy security scenarios.

2015 to 2050, the RESI-based scenarios involve reductions of 74% in RESI_70, 78% in RESI_80 and 87% in RESI_90.

The mound observed in the period 2030–2035 relates again to the installation and use of new natural gas cogeneration plants. On the other hand, the fall around 2040 is due to the retirement of the existing NGCC plants at the end of their lifetime. Finally, small variations (2–4 Mt CO_2 eq) around 2045–2047 are caused by the different contribution from concentrated solar thermal plants with natural gas back-up.

3.4. Further remarks

Beyond the results provided for the case study of power generation in Spain, the methodological framework developed in this study shows high potential for the thorough evaluation of the effects of policies based on energy security targets in other countries or regions. As shown in this work, the extended application of the methodological framework would rely on the formulation of RESI (Section 2.2) as well as on its endogenisation through the "renewable qualification" measures and renewable production targets available e.g. within the LEAP-OSeMOSYS framework (Section 2.3). This would facilitate the discussion about suitable national energy policies and plans, avoiding concerns on short-termism in policy-making [40].

However, it should be acknowledged that, while this approach benefits from the advantages of RESI as an energy security index (practical, easy-to-report, retrospective/prospective, etc.), it also

faces the limitations of RESI as an index [23]. For instance, when taking into account key energy security aspects [9,41,42], the use of RESI directly covers availability and affordability, whereas accessibility and acceptability are only indirectly addressed [23].

Additionally, the application of RESI to the Spanish case study herein involved the use of static values for both β and NRF_i. This means a reasonable simplification regarding import/export electricity balances (being Spanish import/export balances historically below 3% of the national production) and changes in grid transmission losses and life cycle inventories [23].

Finally, it should be acknowledged that the sustainability scope of the assessment could be significantly broadened by addressing a higher number of indicators (e.g., with emphasis on social issues) and/or internalising socio-environmental externalities in the energy systems model [43], which is out of the scope of this article.

4. Conclusions

There are no clear quantitative energy security targets at the country level. This occurs because of the complex nature of the energy security concept, encompassing many different aspects of energy systems (economy, sustainability, efficiency, accessibility, etc.). In this work, through the endogenisation of a policy-oriented index of energy security (RESI) in energy systems models, it was possible to assess prospectively the convenience of energy security-based policies in Spain, focusing on the future role of renewable power generation technologies and the life-cycle implications in terms of both energy security and climate change.

For the case study of power generation in Spain, the application of the novel methodological framework presented in this article showed that energy policies based on ambitious RESI targets would lead to a favourable long-term performance of the national energy system regarding both energy security and climate change. In this sense, the higher the energy security target, the better the system's performance not only from an energy security angle but also from a climate change perspective. This is associated with a severe and relatively fast decarbonisation of the energy system, retiring fossil-based facilities and favouring renewable options with an appropriate trade-off between renewability and costs. This results in a very high contribution of renewable power generation technologies, accounting for above 90% of the national electricity production in 2050 in the evaluated energy security scenarios. In particular, the penetration of renewables is characterised by the great emergence of onshore and offshore wind power generation technologies.

Overall, energy policies based on RESI targets are concluded to be suitable for the Spanish power generation sector. Furthermore, this article paves the way for similar studies to assess prospectively the convenience of energy security-based policies in other regions. In other words, regardless of the geographical scope, future research could benefit from the procedure proposed herein to endogenise energy security targets in energy systems models enriched with a life-cycle perspective.

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